

NONTHERMAL PHENOMENA IN CLUSTERS OF GALAXIES

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Abstract.

Recent observations of high energy (> 20 keV) X-ray emission in a few clusters extend and broaden our knowledge of physical phenomena in the intracluster space. This emission is likely to be nonthermal, probably resulting from Compton scattering of relativistic electrons by the cosmic microwave background radiation. Direct evidence for the presence of relativistic electrons in some ~ 30 clusters comes from measurements of extended radio emission in their central regions. I first review the results from RXTE and BeppoSAX measurements of a small sample of clusters, and then discuss their implications on the mean values of intracluster magnetic fields and relativistic electron energy densities. Implications on the origin of the fields and electrons are briefly considered.

1. Introduction

Extensive X-ray measurements of thermal bremsstrahlung emission from the hot, relatively dense intracluster (IC) gas, have significantly widened our knowledge of clusters of galaxies. Clusters are the largest bound systems in the universe, and as such constitute important cosmological probes. Their detailed dynamical and hydrodynamical properties are therefore of much interest. An improved understanding of the astrophysics of clusters, in particular, a more precise physical description of the IC environment, necessitates also adequate knowledge of the role of nonthermal phenomena. The thermal state of IC gas may be appreciably affected by the presence of magnetic fields, and relativistic electrons and protons. Important processes involving the fields and particles are radio synchrotron emission, X-and- γ -ray emission from Compton scattering of electrons by the cosmic microwave background (CMB) radiation, nonthermal bremsstrahlung, de-

cay of charged and neutral pions from proton-proton collisions, and gas heating by energetic protons. Detection of nonthermal X-ray emission from the electrons, when combined with radio measurements, yields direct information on the particles and fields, and establishes the basis for the study of nonthermal phenomena in clusters.

Clusters directly link phenomena on galactic and cosmological scales. As such, knowledge gained on magnetic fields and cosmic ray energy densities will form a tangible basis for the study of the origin of fields and (relativistic) particles, and their distributions in the intergalactic space. Quantitative information on IC magnetic fields and relativistic electrons is also very important for a realistic characterization of the processes governing their propagation in galactic halos and ejection to the IC space.

Nonthermal X-ray emission has recently been measured in a few clusters by the RXTE and BeppoSAX satellites. While we do not yet have detailed spectral and no spatial information on this emission, we are now able to determine more directly the basic properties of the emitting electrons and magnetic fields. Attempts to measure this emission will continue in the near future; spatial information could be obtained for the first time by observations with IBIS imager aboard the INTEGRAL satellite. In this short review, I describe the current status of the measurement of nonthermal X-ray emission by the RXTE and BeppoSAX satellites, and briefly discuss some of the implications on the properties of relativistic electrons and magnetic fields in clusters.

2. Measurements

2.1. RADIO EMISSION

At present the main evidence for relativistic electrons and magnetic fields in the IC space of clusters is provided by observations of extended radio emission which does not originate in the cluster galaxies. In a recent VLA survey of 205 nearby clusters in the ACO catalog extended emission was measured in 32 clusters (Giovannini et al. 1999, 2000). Only about a dozen of these were previously known to have regions of extended radio emission. In many of the clusters the emitting region is central, with a typical size of $\sim 1-3$ Mpc. The emission was measured in the frequency range $\sim 0.04-1.4$ GHz, with spectral indices and luminosities in the range $\sim 1-2$, and $10^{40.5} - 10^{42}$ erg/s ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

Radio measurements yield a mean, volume-averaged field value of a few μG , under the assumption of global energy equipartition. The field can also be determined from measurements of Faraday rotation of the plane of polarization of radiation from cluster or background radio galaxies (*e.g.* Kim et al. 1991). This has been accomplished statistically, by measuring

the distribution of rotation measures (RM) of sources seen through a sample of clusters. In the recent study of Clarke et al. (2001) the width of the RM distribution in a sample of 16 nearby clusters was found to be about eight times larger than that of a control sample for radio sources whose lines of sights are outside the central regions of clusters. From the measured mean RM, field values of a few μG were deduced.

It should be noted that the above methods to determine the field strength yield different spatial averages. Measurement of synchrotron emission yields a volume average of the field, whereas the measurement of Faraday rotation yields a line of sight average weighted by the electron density.

2.2. NONTHERMAL X-RAY EMISSION

Compton scattering of the radio emitting (relativistic) electrons by the CMB yields nonthermal X-ray and γ -ray emission. Measurement of this radiation provides additional information that enables direct determination of the electron density and mean magnetic field, without the need to invoke equipartition (Rephaeli 1979). In the first systematic search for non-thermal X-ray emission in clusters, HEAO-1 measurements of six clusters with regions of extended radio emission were analyzed (Rephaeli et al. 1987, 1988). The search continued with the CGRO (Rephaeli et al. 1994), and ASCA (Henriksen 1998) satellites, but no significant nonthermal emission was detected, resulting in lower limits on the mean, volume-averaged magnetic fields in the observed clusters, $B_{rx} \sim 0.1 \mu\text{G}$.

Significant progress in the search for this emission was recently made with the RXTE and BeppoSAX satellites. Evidence for the presence of a second component in the spectrum of the Coma cluster was obtained from RXTE (~ 90 ks PCA, and ~ 29 ks HEXTE) measurements (Rephaeli et al. 1999). Although the detection of the second component was not significant at high energies, its presence was deduced at energies below 20 keV. Rephaeli et al. (1999) argued that this component is more likely to be nonthermal, rather than a second thermal component from a lower temperature gas. The two spectral components and the measurements are shown in Figure 1. The best-fit power-law photon index was found to be 2.3 ± 0.45 (90% confidence), in good agreement with the radio index. The 2-10 keV flux in the power-law component is appreciable, $\sim 3 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. The identification of the flux measured in the second component as Compton emission, when combined with the measured radio flux, yields $B_{rx} \sim 0.2 \mu\text{G}$, and an electron energy density of $\sim 8 \times 10^{-14} (R/1\text{Mpc})^{-3} \text{ erg cm}^{-3}$, scaling the radial extent (R) of the emitting region to 1 Mpc.

Observations of the Coma cluster with the PDS instrument aboard the BeppoSAX satellite have led to a direct measurement of a power-law compo-

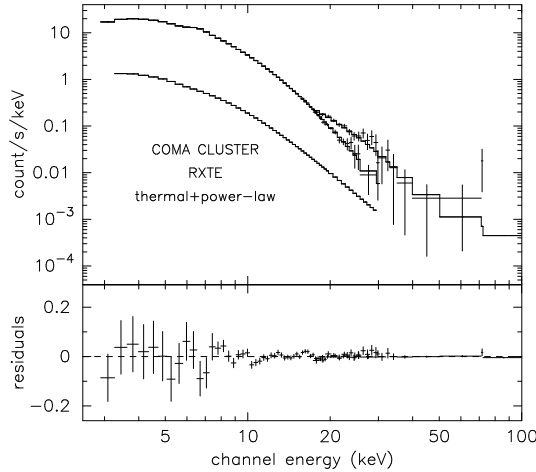


Figure 1. RXTE spectrum of the Coma cluster. Data and folded Raymond-Smith ($kT \simeq 7.51$ keV), and power-law (index = 2.34) models are shown in the upper frame; the latter component is also shown separately in the lower line. Residuals of the fit are shown in the lower frame.

nent at high energies, 25 – 80 keV (Fusco-Femiano 1999). A best-fit power-law photon index 2.6 ± 0.4 (90% confidence) was deduced. The measured flux in a 20-80 keV band is $\sim 2 \times 10^{-11}$ erg cm $^{-2}$ s $^{-1}$, about $\sim 8\%$ of the main, lower energy 2-10 keV flux. A Compton origin yields $B_{rx} \sim 0.15$ μ G. These results are in good general agreement with the RXTE results (Rephaeli et al. 1999). In addition to Coma, power-law components were measured by BeppoSAX in two other clusters, A2199 (Kaastra et al. 2000), and A2256 (Fusco-Femiano 2000). RXTE measurements of a second cluster, A2319, have also yielded evidence for a second spectral component (Gruber & Rephaeli 2001). Note that A2199 is not known to have an extended region of IC radio emission.

While the measurements of second components in the spectra of these four clusters are significant, the identification of the emission as nonthermal is not certain. To better establish the nature of this emission, spatial information is needed in order to determine the location and size of the emitting region. The large fields of view of the RXTE ($\sim 1^\circ$) and BeppoSAX/PDS ($\sim 1.3^\circ$) instruments do not allow definite identification of the origin of the observed second spectral components. What seems to have been established, however, is that there is no temporal variability in the RXTE and BeppoSAX data, so an AGN origin of the second spectral components in these clusters is unlikely.

3. Theory

3.1. MAGNETIC FIELDS

The origin of IC magnetic fields is of interest in the study of the evolution of the IC environment and of fields on cosmological scales. IC fields could possibly be of cosmological origin – intergalactic fields that had been enhanced during the formation and further evolution of the cluster, or else the fields might be mostly of galactic origin. The latter is a more likely possibility: fields were anchored to (‘frozen in’) the magnetized interstellar gas that was stripped from the member (normal and radio) galaxies (Rephaeli 1988). Dispersed galactic fields would have lower strengths and higher coherence scales in the IC space than is typical in galaxies. The field strength can be estimated under the assumption of flux-freezing, or magnetic energy conservation, if re-connection is ignored. Since typical galactic fields are \sim few μ G, mean volume-averaged field values of a few 0.1μ G are expected in the IC space. It is possible that Fields may have been amplified by the hydrodynamic turbulence generated by galactic motions (Jaffe 1980). However, this process was found to be relatively inefficient (Goldman & Rephaeli 1991) in the context of a specific magneto-hydrodynamic model (Ruzmaikin et al. 1989).

Estimates of magnetic fields in extended sources are usually based on measurements of the synchrotron emission by relativistic electrons, and by Faraday rotation measurements. The estimates of B_{rx} quoted in the previous section - based on radio synchrotron and Compton emission by what was *assumed* to be the same relativistic electron population - are quite uncertain due to the need to make also other assumptions, such as the equality of the spatial factors in the expressions for the radio and X-ray fluxes (Rephaeli 1979). These are essentially volume integrations of the profiles of the electrons and fields, and since we have no information on the X-ray profile - and only rudimentary knowledge of the spatial distribution of the radio emission - this ratio was taken to be unity in the above mentioned analyses of RXTE and BeppoSAX data. The effect of this assumption is a systematically lower value of B_{rx} .

Faraday rotation measurements yield a weighted average of the field *and* gas density along the line of sight, B_{fr} . Estimates of B_{fr} are also substantially uncertain, due largely to the fact that a statistically significant value of RM can only be obtained when the data from a sample of clusters are superposed (co-added). The significantly broader distribution of RM when plotted as function of cluster-centric distance clearly establishes the presence of IC magnetic fields. However, the deduced mean value of B_{fr} is an average over all the clusters in the sample, in addition to being a weighted average of the product of a line of sight component of the field

and the electron density. Both the field and density vary considerably across the cluster; in addition, the field is very likely tangled, with a wide range of coherence scales which can only be roughly estimated (probably in the range of $\sim 1 - 50$ kpc). All these make the determination of the field by Faraday rotation measurements considerably uncertain.

The unsatisfactory observational status, and the intrinsic difference between B_{rx} and B_{fr} , make it clear that these two measures of the field cannot be simply compared. Even ignoring the large observational and systematic uncertainties, the different spatial dependences of the fields, relativistic electron density, and thermal electron density, already imply that B_{rx} and B_{fr} will in general be quite different. This was specifically shown by Goldshmidt & Rephaeli (1993) in the context of reasonable assumptions for the field morphology, and the known range of IC gas density profiles. It was found that B_{rx} is typically expected to be smaller than B_{fr} . Improved measurement of the spatial profile of the radio flux, and at least some knowledge of the spatial profile of the nonthermal X-ray emission, are needed before we can more meaningfully establish the relation between B_{rx} and B_{fr} in a given cluster.

3.2. ENERGETIC PARTICLES

The radio synchrotron emitting relativistic electrons in clusters lose energy also by Compton scattering. Where the field is $B < 3 \mu\text{G}$, Compton losses dominate, and the characteristic loss time is $\tau_c \simeq 2.3/\gamma_3$ Gyr, where γ_3 is the Lorentz factor in units of 10^3 . Such electrons have Lorentz factors $\gamma_3 > 5$, if $B \sim 1 \mu\text{G}$, and therefore they lose their energy in less than 1 Gyr. If the mean field value is lower than $1 \mu\text{G}$, then the Compton loss time is even lower, because higher electron energies are needed to produce the observed radio emission. Clearly, if most of the radio-producing electrons had been injected from galaxies during a single, relatively short period, then the observed radio emission is a transient phenomenon, lasting only for a time $\sim \tau_c$, which is typically less than 1 Gyr. In this case the electron energy spectrum evolves on a relatively short timescale, shorter than typical evolutionary times of normal galaxies. It follows that electrons from an early injection period would have lost their energy by now. If the emission is indeed relatively short-lived, then it may possibly be related to a few strong radio sources.

On the other hand, if the observed radio emission has lasted more than a Compton loss time, then the relativistic electron population has perhaps reached a (quasi) steady state. This could be attained through continual ejection of electrons from radio sources and other cluster galaxies, or by re-acceleration in the IC space. The lower the mean value of the field, the

shorter has the electron replenishment time to be. It is unclear whether any of these is a viable possibility, particularly so in the case of sub- μG fields. For electrons with energies $\ll 1$ GeV, the main energy loss process is electronic (or Coulomb) excitations (Rephaeli 1979), and the loss time is maximal for $\gamma \sim 300$ (Sarazin 1999). In order for electrons with energies near this value to produce the observed IC radio emission, the mean magnetic field has to be at least $\sim \text{few } \mu\text{G}$. But in this case Compton scattering of these electrons by the CMB would only boost photon energies to the sub-keV range.

Various models have been proposed for acceleration of electrons in the IC space. All these invoke different scenarios of acceleration by shocks, resulting from galactic mergers, or shocks produced by fast moving cluster galaxies. In some of the accelerating electron models that have been proposed (Kaastra et al. 1998, Sarazin & Kempner 2000), electrons produce (nearly) power-law X-ray emission by nonthermal bremsstrahlung. Presumably, all the radio, EUV, and X-ray measurements of Coma and A2199 can be explained as emission from a population of accelerating electrons (Sarazin & Kempner 2000). However, the required electron energy density is much higher than in the relativistic electron population that produces power-law X-ray emission by Compton scattering (Rephaeli 2001, Petrosian 2001). A more plausible acceleration model has been suggested by Bykov et al. (2000). In their model, galaxies with dark matter halos moving at supersonic (and super-Alfvénic) velocities can create collisionless bow shocks of moderate Mach number $M \geq 2$. Kinetic modeling of non-thermal electron injection, acceleration and propagation in such systems seem to demonstrate that the halos are efficient electron accelerators, with the energy spectrum of the electrons shaped by the joint action of first and second order Fermi acceleration in a turbulent plasma with substantial Coulomb losses. Synchrotron, bremsstrahlung, and Compton losses of these electrons were found to produce spectra that are in quantitative agreement with current observations.

Although we do not yet have direct evidence for the presence of a substantial flux of energetic protons in the IC space, we do expect (based on the fact that protons are the main Galactic cosmic ray component) that they contribute very significantly - and even dominate - the cosmic ray energy density in clusters. Models for relativistic IC protons (Rephaeli 1987) and their γ -ray emission by neutral pion decays (produced in p-p collisions), or by the radiation from secondary electrons resulting from charged pion decays, have been proposed (Dermer & Rephaeli 1988, Blasi & Colafrancesco 1999). A substantial low-energy proton component could also cause appreciable (Coulomb) heating of the gas in the cores of clusters (Rephaeli 1987, Rephaeli & Silk 1995).

4. Conclusion

Recent RXTE and BeppoSAX measurements of power-law X-ray emission in four clusters improve our ability to characterize extragalactic magnetic fields and cosmic ray electrons. As expected, clusters of galaxies provide the first tangible basis for the exploration of nonthermal phenomena in intergalactic space. The radio and X-ray measurements strongly motivate further work on these phenomena. With the moderate spatial resolution (FWHM ~ 12 arcminute) capability of the IBIS imager on the INTEGRAL satellite (which is scheduled for launch in 2002) it will be possible to determine the morphology of nonthermal (at energies > 15 keV) emission in nearby clusters. Such spatial information is crucial for a more definite identification of the observed second X-ray spectral components. Unequivocal measurement of cluster nonthermal X-ray emission will greatly advance the study of nonthermal phenomena on cosmological scales.

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